APPLICATION OF AIRBREATHING PROPULSION TO REUSABLE LAUNCH VEHICLES*

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ABSTRACT

Mission and performance requirements are briefly reviewed to provide proper context for information given. The principal mission considered is logistics operations to Earth orbit. Second stages are assumed to be reusable, cryogenic, rocket propelled, lifting bodies or wing-bodies. Attention is concentrated on the propulsion options for the reusable first stage. The paper gives results of semi-quantitative comparison studies using a matrix of criteria. It is shown that under certain combinations of assumptions and criteria, rocket propelled first stages may be preferable to airbreathing first stages. Frequently a mixture of rocket and air-breathing propulsion will appear preferable. The influence of mission requirements is illustrated.

INTRODUCTION

Reusable space launch vehicles have been studied since long before the first artificial Earth satellite. At the present, there is no approved program for a reusable launch vehicle, but we are still studying them and the session of the AIAA Propulsion Specialists' Conference in which this paper was presented discussed that class of reusable launch vehicles which are airplane-like in their operation. (The word "we" here means the technical community within the United States.) It has been stated that ** "spacecraft are not aircraft," and yet it would seem that this is a pity when we note the difference in cost and difficulty of operating space-craft as compared to aircraft. The launch vehicles which will be discussed in this session represent conceptually an attempt to reduce the cost of space launches by imitating airplanes with their high degree of reusability, and an attempt to devise a vehicle of great utility and versatility.

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In a vehicle of this type, it seems only natural to employ as first stage primary propulsion, airbreathing engines of one sort or another. Indeed, many studies have shown that such use of airbreathing propulsion will result in substantial reductions in vehicle liftoff weight; the amount of reduction seems to be roughly a function of the assumed state-of-the-art of airbreathing propulsion. It is unfortunately not clear that the airbreathing first stage with its reduced gross weight is a more desirable vehicle, as will be discussed.

This paper will not discuss technical matters relating to employment of airbreathing propulsion in reusable launch vehicles; rather it is an inquiry into the problem of deciding whether or not airbreathing propulsion should be used, and if so, in what form. No solutions to this vexing question will be given, but it is hoped at least to illustrate the nature of the problem. In the course of so attempting, certain facts and observations which are obvious will be stated; in the writers' opinion they are worth reiterating.

Until recently the prime, and often only, explicit criterion used to judge space launch systems has been initial gross weight required to accomplish the given mission. It seems likely that for many people, use of this criterion appeared to circumvent many of the problems of personal opinion involved in selecting a design concept. However, applicability of gross weight as a prime criterion is itself a matter of opinion. Although convenient and explicit, it is not directly related to what is really desired from a vehicle system. It can be recognized that there are in fact a great many selection criteria which should be given consideration. The pertinent problems are: what are the criteria?; how should their relative importance be considered?; how should they be used in making a selection?; how do they relate to mission objectives?

The purpose of this paper, stated more specifically, is to discuss the relationships between the propulsion-type in the first stage of a two-stage reusable launch vehicle and the various concept selection criteria which might be employed, and the mission requirements which might be imposed on such a vehicle. It is important to recognize that trends indicated by this paper are very strongly influenced by the mission assumptions; that no definitive set of mission assumptions exists; that no definitive set of criteria or generally agreed upon method of employment of criteria exists; and

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therefore conclusions as to "best" vehicles cannot be drawn herein. It is hoped, however, to convey the general types of considerations implied by these factors.

DEFINITION OF MISSION MODEL AND LAUNCH VEHICLE TYPE

It is to be expected that the determination of a "best" launch vehicle in the reusable category will be very sensitive to the detailed description of the mission and requirements for the vehicle. For this reason, it is necessary to include in this paper a summary description of a mission model and related vehicle requirements in order that indicated trends may be placed in proper perspective.

It is assumed that the principal mission for the reusable launch vehicle would be logistics resupply and crew rotation for manned orbiting laboratories in rendezvous compatible orbits. The nominal orbit is at a 485-kilometer altitude and is inclined at 30.5° to the equator. Orbital research laboratories of various descriptions and perhaps an orbital launch facility are implied. Detailed nature of these facilities is not of concern to this paper. An additional requirement to service orbiting laboratories in polar orbit is assumed. A further typical mission considered is delivery to orbit of small instrumented satellites and probes with or without additional propulsive stages, depending on the mission requirement. Implicit in this mission is the assumed capability to provide final checkout and adjustment of the satellite after attaining orbit.

A considerable variety of missions might be considered as potentially to be performed by a reusable launch vehicle of the general type under discussion. However, the larger the number of distinct mission profiles to be considered as requirements, the greater will be the penalty which must be accepted in terms of capability to do in an optimal manner an individual mission. As an extreme example, if one demanded that the vehicle be capable of transporting a crew to a synchronous orbit, one would certainly find the vehicle vastly overdesigned for crew transport to low Earth orbit. A reasonable first-cut approach to this problem appears to be to design the vehicle principally around those missions for which it will be most used, accepting degraded performance (or even incapability) for those missions for which it would be used rarely. This approach, unfortunately, requires a reasonably well-defined mission model, something which does not exist. Therefore, a purely hypothetical model has been postulated to serve as an example. Its characteristics are given in Table 1.

TABLE 1

HYPOTHETICAL MISSION MODEL FOR REUSABLE AEROSPACE PERSONNEL TRANSPORT

DELTA V CLASS	MISSION TYPE	FLIGHT FREQUENCY, Per Year		REMARKS
		Conservative	Optimistic	
Low (includes roughly 50 miles cross-range)	Low-inclination orbit space station logistics	10	50	Baseline mission for design. Includes orbital launch facility support.
	Astronaut training	10	25	Military and civilian
	Low-altitude reconnaissance	15	30	Military and civilian. Payload trades for orbital stay time.
	Delivery and retrieval of small satellites to or from low orbit	25	50	Payload up to roughly 10,000 lb - may include propulsive "kick" stage
	International traffic - satellites and astronauts	10	50	May depend on Russian capability to offer competition.
Medium (50 miles cross-range)	Polar orbit space station logistics	10	25	Passenger capacity and payload reduced.
	Delivery of small satellites to long-life or polar orbit	10	20	Roughly 2000 - 5000 lb. payload.
High (600 miles cross-range desirable)	Rapid rendezvous, low or medium altitude orbits	5	20	Requires alternate upper stages, expendable/reusable
Impractical	Synchronous orbit logistics; lunar, planetary missions	-	-	Beyond capability of this type of vehicle. See "Diet Smith."
	TOTALS	95	270	

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It is intended to indicate possible distribution of traffic a few years after a reusable vehicle would begin flying, so that utilization of the vehicle had reached some maturity. The conservative model assumes that the effect of availability of this vehicle's capability on the traffic is slight; the optimistic, that the effect is large.

The following vehicle requirements have been used in the subject studies; although they are in part arbitrary they have proven quite useful.

     a. Provision of shirt-sleeve atmosphere for crew of two and ten passengers for 2 days.

     b. Three metric tons of stowed cargo deliverable either directly to the space environment or through the crew and passenger compartment to an orbiting laboratory.

     c. For polar orbit missions, a passenger complement of six and a cargo capacity of one metric ton.

     d. Provision for rendezvous and docking with an orbital laboratory. Rapid rendezvous, as in certain possible military applications, is not assumed as a requirement.

     e. Provision for retrograde impulse to initiate controlled reentry.

     f. Capability to make controlled reentry with horizontal landing at a pre-determined site, carrying the full complement of crew, passengers, and cargo.

     g. During normal operations, subjection of the crew and passengers to no more than 3 g's net acceleration during any part of the mission.

     h. Crew and passenger survival probability of .999 for any one mission.

     i. Vehicle configuration of two stages, both fully recoverable and reusable with minimum-cost refurbishment.

As the purpose of this paper is to discuss airbreathing propulsion in the first stage, a brief description of a typical upper stage concept is in order.

Figure 1 depicts the typical upper stage. It is a lifting body with integral crew, passenger, and cargo compartment, and advanced technology oxygen-hydrogen propulsion system. Nominal staging conditions are a relative velocity of 2.08 km per second at an altitude of 53.8 km. The nominal total ideal velocity requirement for this stage is 6.351 km per second, of which 60 meters per second are provided by the auxiliary storable propulsion system which is used for final rendezvous and docking. Various first stage designs may, in general, have differing optimal staging
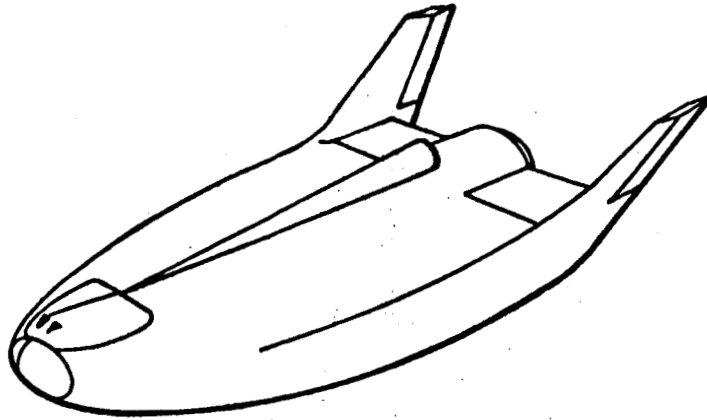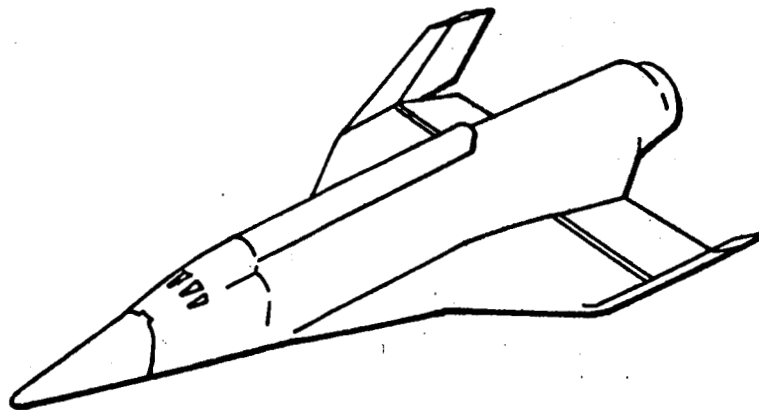
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FIGURE 1.　　TYPICAL LIFTING BODY SECOND STAGE

FIGURE 2.　　TYPICAL WING BODY SECOND STAGE

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velocities. Figure 2 shows an alternate second stage configuration, a wing-body which might integrate better with an airbreathing first stage, if external installation is desired.

DISCUSSION OF CRITERIA AND THEIR APPLICATION

In order to provide some small degree of clarity to this discussion, it was necessary to choose a list of typical criteria and run through some comparison exercises with them. There are a large number of criteria which could conceivably be applied to a process of decision-making in selecting a launch vehicle concept and configuration. Those criteria to be discussed in the following are not purported to be an exhaustive list, but they are at least typical and will exemplify the intended points. They are defined in order to insure understanding of what each means to the writers.

     a. Cost effectiveness as a criterion implies the ability of a vehicle system to perform its mission at less cost than competitive systems. Typical cost effectiveness definitions are dollars per pound of useful payload delivered to orbit or other intended destination, computed either on direct operating cost, or on total operating cost, including RDT&E of the vehicle system. Dollars per launch might be useful in certain applications. Cents per ton mile or dollars per passenger mile are valuable in analysis of systems whose departure points and destination are on the Earth's surface. Dollars per man round trip or dollars per man hour in space are more examples of cost effectiveness criteria. For a logistics application of the launch vehicle, the most valuable cost effectiveness criteria would appear to be dollars per man round trip to orbit and dollars per man hour supported in orbital activity. Both direct operating cost and total operating cost are of interest.

     b. The value of gross weight as a criterion is principally in its relative ease of estimation and direct physical meaning. Gross weight may be compared either absolutely where a given mission and payload are common to all systems, or more generally, in terms of gross weight divided by payload or some other mission accomplishment parameter.

     c. The importance of reliability is relatively obvious.

     d. Capability to do alternate missions is of considerable importance for the class of vehicle being discussed here. The baseline mission group has

been described; some additional alternate missions which might be considered are hypersonic flight research and propulsion test vehicle, and VIP rapid long range transport.

e. For manned vehicles, crew and passenger safety is obviously of paramount importance.

f. Development risks can take two meanings, the first of which is: "how likely is the final product to be capable at all of the intended mission?" and secondly, "how likely is it that the development cost and schedule will be kept under control?"

g. Growth potential implies the capability by an orderly process of design improvements to extend the performance of the system.

h. Schedule compatibility asks whether the required technologies for this vehicle system design are sufficiently well in hand that the vehicle can be developed and operational by the time it is needed. In this paper, for purposes of illustration, it was assumed that a reusable launch vehicle was desired in ten to twelve years.

i. Development cost is a criterion which should be considered separately from cost effectiveness since the absolute magnitude of the estimated development cost (irrespective of possible cost effectiveness advantages) will have a considerable effect on the process of management decision to proceed with development.

j. Specifically applicable to the type of vehicle being considered here is the question of second stage compatibility. This implies the adaptability of the first stage to a variety of second stage configurations. This is an important point; it is related to the criterion of alternate missions, and will be discussed in more detail separately.

k. Another criterion which is called in this paper, acceptance, asks whether the particular configuration is one which is generally liked in the technical community. Correlation of this item with the other attributes of a given concept may be weak. The criterion is important because some degree of consensus in the cognizant technical community is frequently required to achieve approval of a development program.

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l. Contributions to technology indicate the degree to which development of a given configuration would advance technology.

m. Finally, we get into the class of criteria which might be called operational characteristics. Those considered here are ground noise environment, sonic boom, staging conditions, abort capability, refurbishment and turn-around, launch window flexibility, and launch off-set flexibility.

It is, of course, clear that there exists a considerable degree of interaction among these various criteria. They are by no means independent. For example, consider the interrelations between staging conditions, abortability, reliability, and safety. It should be also recognized that certain of these criteria or combinations thereof may act as rejection filters; this characteristic is not adequately represented by the weighting procedure to be discussed. For example, consider the interrelation between alternate mission requirements and sonic boom characteristics. If the alternate missions require the vehicle to overfly population centers, and if a given concept (otherwise very favorable) has high sonic over-pressure characteristics, then public unacceptability requires this vehicle concept to be eliminated. This rejection filter characteristic should be recognized as extremely important, and requiring separate consideration in any process of comparison by weighting factors and judgment.

It is further the writers' experience that, in making a comparison study utilizing a large number of criteria, it is definitely possible, consciously or unconsciously, to slant the results by the choice of criteria. For example, if instead of listing cost effectiveness as a single general criteria, we had selected a variety of specific measures of cost effectiveness such as dollars per pound in orbit, dollars per launch, and some of the others previously mentioned, the results would be biased to a greater degree toward those vehicles which are more cost effective. A rational way of dealing with this problem is not immediately apparent.

The list of criteria used in this study is repeated in Table 2 along with selected weighting factors which are employed to bias the selection in various ways. These weight factors indicate the importance of the respective criteria; larger numbers giving greater weight. The weight factors are employed in manipulation of the

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TABLE 2

TYPICAL WEIGHT FACTOR DISTRIBUTIONS

Criterion	Nominal Weight	Balanced Weight	Operational Enhanced	Cost and Program Enhanced	Safety Enhanced
Cost Effectiveness	1	7	5	10	
Gross Weight	1	5	7		
Reliability	1	7	8	10	10
Alternate Missions	1	5	10		
Safety	1	10	8	10	10
Development Risk	1	8	8	10	
Growth Potential	1	5	10		
Noise	1	3	7		
Sonic Over-Pressure	1	4	7		
Staging Conditions	1	3	7		10
Abortability	1	5	7		10
Refurbishment and Turn-Around	1	4	7	10	
Launch Window	1	3	7		
Launch Offset	1	3	7		
Schedule Compatibility	1	8	5	10	
Total Development Cost	1	10	5	10	
Upper Stage Compatibility	1	5	10		
Acceptance	1	6	3		
Contributions to Technology	1	8	3		

criteria matrix of Table 5, as is explained further below. "Balanced weight" indicates the writers' overall preference in selection of weighting factors. The last two weight factor distributions represent simpler arrangements ignoring all but primary criteria.

FIRST STAGE CANDIDATES

A total of eight first stage system candidates were considered. Again, this is not purported to be an exhaustive list, but is illustrative. Table 3 lists the candidates with their principal assumed characteristics. There are two all-rocket versions, one air-augmented rocket, four air-breather hybrids, and one all-airbreather. Air liquefaction and separation systems and supersonic combustion ramjets were not considered. The air-augmented configuration was assumed to employ "simple" air augmentation; i.e., fixed geometry and simultaneous mixing and expansion.

Before making comparisons on the basis of given criteria, it is useful as a preliminary step to consider advantages and disadvantages of airbreathing first stages in a general way. This is done in Table 4. Since there seems to exist a continuum of vehicle concepts from all-rocket to all-airbreather, the list in Table 4 should be thought of as representative only.

RESULTS OF CRITERIA MATRIX

In order to make a weighting factor comparison, the criteria are listed in a matrix with the vehicle configurations which we desire to compare, such as has been done in Table 5. Attached to each of the criteria is a weighting factor from one of the groups of Table 2 or some similar group, which represents in the analyst's judgment the relative importance of that particular criterion. Absolute magnitude of these weighting factors is of course unimportant; only the relative values affect the outcome. Numbers in the matrix itself are again judgment numbers. In this case they represent, in the opinions of the writers, how well each of the configurations satisfies a given criterion. As applied in the example, larger numbers represent a better match. As a specific example, in Table 5 under the heading

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TABLE 3

| Candidate	Rocket Engines	Air-Breather Engines	Estimated Vehicle Gross Wt.	Figure No.
Lox/RP-1 Rocket	F-1 and H-1	(Flyback)	1.6×10^6 lb	3
Lox/RP-1 Rocket, Air Augmented	H-1	Augmentation Duct Acts as Ramjet for Flyback	1.5×10^6 lb	4
Lox/LH$_2$ Rocket	J-2	for LH$_2$ (Flyback)	1.2×10^6 lb	-
SST/RP-1 with Rocket	H-1	SST	1.9×10^6 lb	5
SST/LH$_2$ with Rocket	J-2	SST Mod. for LH$_2$	1.0×10^6 lb	-
Turboramjet with Rocket	J-2	(Fuel-rich Fan)	0.8×10^6 lb	-
Rocket/Ramjet	J-2	LH$_2$ Ramjet	1.0×10^6 lb	-
Turboramjet No Rocket	None	(Fuel-rich Fan)	0.6×10^6 lb	6
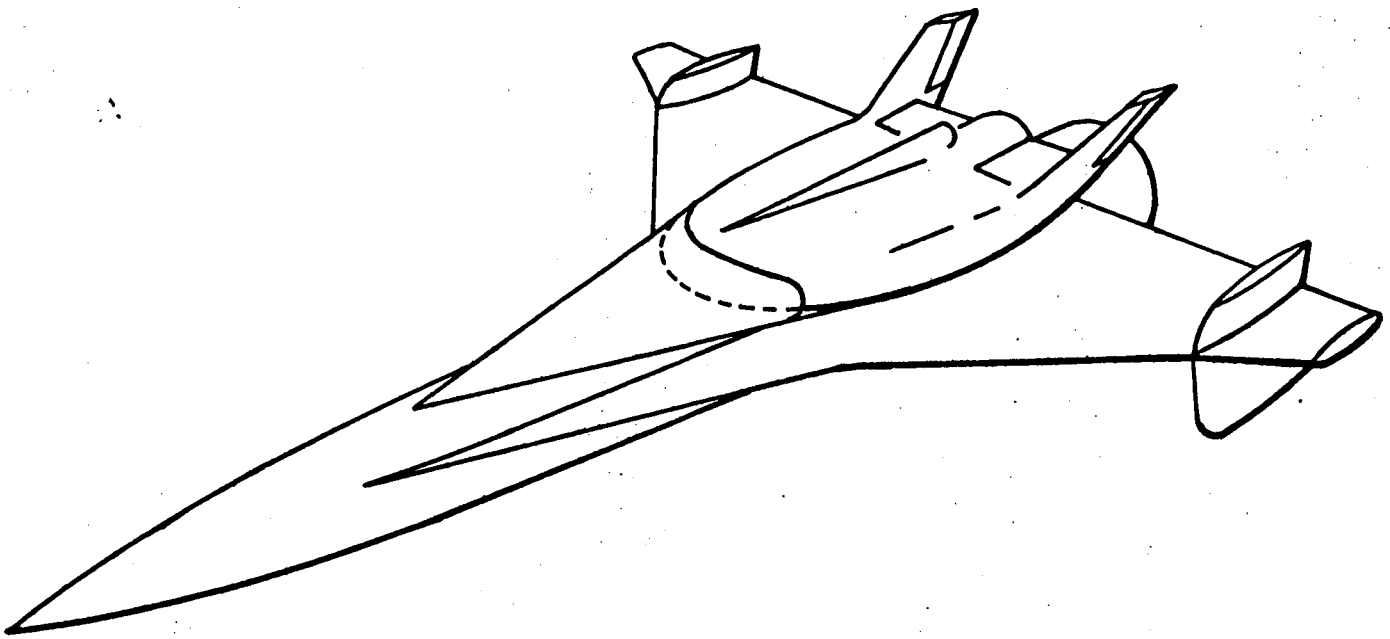
FIGURE 3.   LOX/RP-1 ROCKET FIRST STAGE

A lifting body second stage is shown installed with a drag-reduction
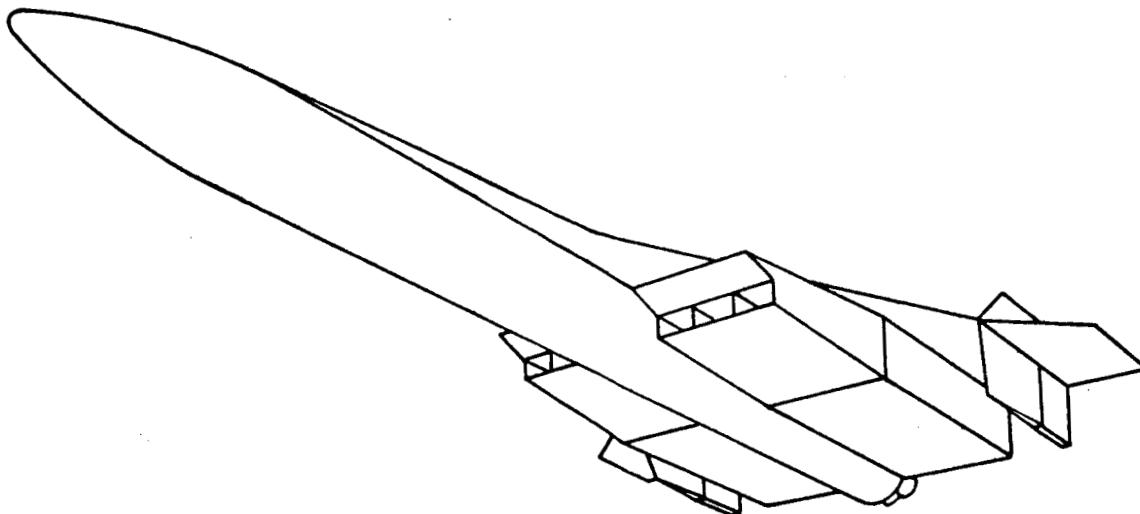fairing.

FIGURE 4.   LOX/RP-1 ROCKET FIRST STAGE WITH AIR AUGMENTATION

This stage concept employs eight H-1 engines, six of which are installed in the air augmentation ducts. The two remaining H-1's are located in the boattail in order to provide thrust vector control.
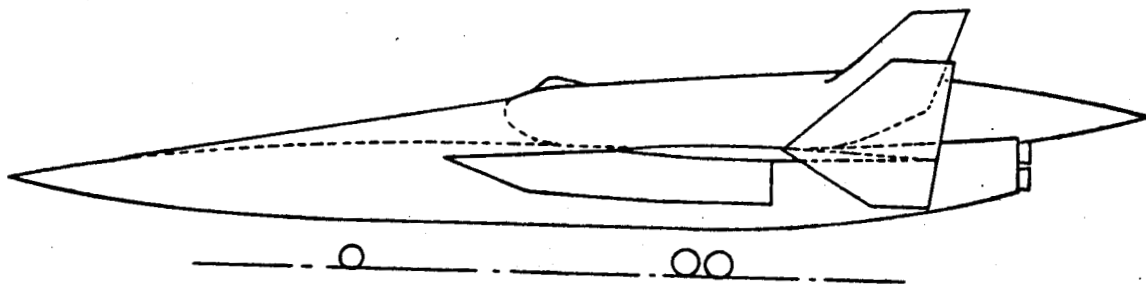
FIGURE 5.   SST/RP-1 AIRBREATHER FIRST STAGE WITH LOX/RP-1 ROCKETS.

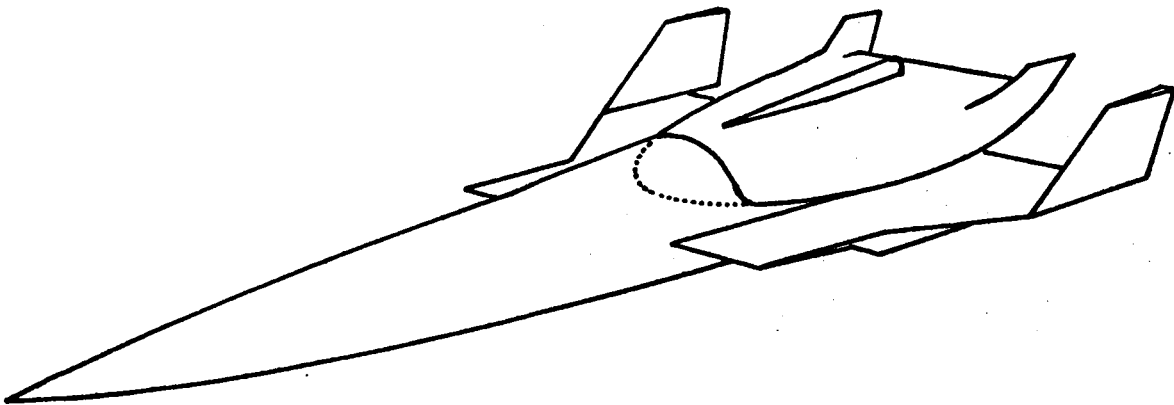A lifting body upper stage with fore and aft fairings is shown installed.

FIGURE 6.   HYDROGEN TURBORAMJET FIRST STAGE

A lifting body upper stage is shown partially buried in a
fuselage cavity of the first stage. This stage integration
concept is feasible because of the large volume of low-
density liquid hydrogen required.

TABLE 4

ADVANTAGES AND DISADVANTAGES OF ADVANCED AIR-BREATHERS IN

FIRST STAGE

(As Compared to All-Rocket First Stage)

A. ADVANTAGES
1. Lower gross weight.
2. Adaptable to runway take-off with moderate initial weight penalty.
3. Greater cross-range and dogleg capability at a given initial weight penalty.
4. High Mach number cruise capability for alternate missions.
5. (Probably) less refurbishment for reuse. (Refers to engines only.)
6. (Probably) greater likelihood of successful abort, if required.
7. (Possibly) greater contribution to future air transport technology.
B. DISADVANTAGES
1. Require liquid hydrogen in first stage.
2. More problems with sonic overpressure.
3. Not adaptable to vertical takeoff (unless rocket boost is used).
4. Very sensitive to overall vehicle drag; thus, not readily adaptable to alternate upper stages.
5. More severe thermal environment during boost.
6. Engine development needs ground test facilities not presently available.
7. (Probably) higher unit cost for first stage.

TABLE   5
CRITERIA MATRIX

Criterion	WT	LOX/RP-1 ROCKET	LOX/RP-1 RKT with AIR AUGM.	LOX/LH$_2$ ROCKET	SST/RP-1 A/B+ ROCKET	SST/LH$_2$ A/B+ ROCKET	TURBORAMJET + ROCKET: LH$_2$	ROCKET - RAMJET: LH$_2$	FRF-TRJ: LH$_2$ no ROCKET
Cost Effect-iveness		10	7	9	2	5	6	8	8
Gross Weight		4	5	6	2	6	8	6	10
Reliability		10	8	9	6	5	6	7	8
Alternate Missions		5	5	6	8	6	6	6	7
Safety		7	5	7	4	6	10	7	8
Development Risk		9	5	8	5	4	4	7	4
Growth Potential		5	6	7	3	10	7	9	6
Noise		9	8	9	5	6	7	10	7
Sonic Overpress.		10	10	10	0	2	3	10	5
Staging Conditions		10	10	10	10	10	10	10	6
Abortability		4	4	4	8	8	9	6	10
Refurbish. & Turnaround		9	2	10	5	7	7	7	8
Launch Window		4	6	5	8	6	6	7	9
Launch Offset		2	2	3	8	5	6	6	7
Schedule Compat.		10	6	9	5	5	3	7	3
Development Cost		10	6	9	3	3	1	7	4
Upper Stg Compat.		10	5	10	1	2	3	5	3
Acceptance		4	6	5	3	6	10	9	8
Contrib. to Technology		4	6	5	5	7	10	8	8

TABLE 6

RESULTS OF CRITERIA ANALYSIS

WEIGHTING POLICY	LOX/RP-1 ROCKET	LOX/RP-1 ROCKET WITH AIR AUG.	LOX/LH$_2$ ROCKET	SST/RP-1 WITH ROCKET	SST/LH$_2$ WITH ROCKET	FUEL-RICH FAN-RAMJET WITH ROCKET	ROCKET RAMJET	FUEL-RICH FAN-RAMJET WITHOUT ROCKET
NOMINAL	134	112	141	91	109	122	142	128
BALANCED	811	638	818	487	601	682	802	719
OPERATIONAL	950	764	993	636	754	822	963	886
COST AND PROGRAM	580	340	530	260	290	270	430	430
SAFETY	300	270	300	280	290	350	300	320

"gross weight," since it was indicated in Table 3 that the turboramjet first stage without rocket propulsion was the minimum gross weight vehicle; this concept received the highest score.

Numbers assigned to the matrix by the writers were, to a considerable degree, intuitive; they were based in a few cases on a variety of study reports, papers, and documents, which were not necessarily based on the same ground rules and assumptions. It is possible to synthesize a method for using definite numerical values in the matrix, related to performance, operational, and cost parameters. Boeing, in a study under contract NAS8-11429, has done this, although with a different list of criteria, a different set of candidate vehicles, and deriving somewhat different results. Their investigation considered all features of vehicle designs, rather than just first stage propulsion. A method using definite data will, in general, require a substantial depth of study on each configuration considered.

Use of the criteria matrix consists of multiplying numbers in the matrix by their corresponding weighting factors. Columns of the resulting matrix are then summed to arrive at "figures of merit." For the nominal case, where all weighting factors are unity, columns in the original matrix are directly summed. Results for each of the weighting policies of Table 2 are given in Table 6.

DISCUSSION

This discussion, as it relates to the results of the criteria matrix and where it indicates trends or conclusions, must be considered as tentative and regarded with caution for several reasons; (a) the results are based on the writers' opinions; (b) certain possible first-stage propulsion options such as scramjet, air collection systems, advanced composite engines, or storable rocket propellants were not considered, (c) available data were incomplete in certain cases, (d) comparisons were confined to two-stage, fully reusable systems. Alternate possibilities involving expendable stages, or more than two stages were not considered, and (e) it represents an assessment at a particular point in time. Further study, new data, and maturing of new technology will influence and change the results.

No concept was found which excelled in satisfying all criteria. It is believed

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that this statement could be made general to include concepts not investigated. Some concepts tend to be very good in certain areas and quite poor in others while other concepts have a more "balanced" characteristic. This may be of some significance in indicating the improbability of creating a vehicle concept in this class of vehicles which will satisfy everyone. Compromises appear to be important.

The most consistent high "figures of merit" were shown by the all-rocket systems, which appeared to be slightly superior to the rocket-ramjet. Also appearing rather favorable were the fuel-rich turbofan systems. The Lox-hydrogen rocket retains most of the advantages of the all-rocket system, which lie basically in the areas of simplicity and directness of development program, and lack of certain operational problems, such as sonic over-pressure and sensitivity to drag variations caused by substitution of alternate upper stages. At the same time, by virtue of the higher performance of Lox-hydrogen enough vehicle performance margin may be provided to alleviate problems of sensitivity to inert weight changes and to allow a very limited amount of cross-range and dog-leg capability. The Lox-hydrogen rocket is also appreciably lower in gross weight than the Lox/RP-1 rocket. Its disadvantages compared to the Lox/RP-1 rocket are principally the required insulation and structural problems in the first stage due to the deep cryogenic; larger vehicle volume, and slightly higher propellant costs. The rocket-ramjet offers an interesting compromise between air-breather characteristics and rocket characteristics. The ramjet is somewhat simpler than airbreathers with advanced rotating machinery and should cost less to develop. While this scheme shows a higher gross weight than turboramjet systems, the difference is essentially all propellant, rather than hardware weight and, thus, is not necessarily reflected in terms of system costs. The rocket-ramjet could take off vertically if desired and can be expected to minimize sonic over-pressure problems at less penalty than associated with turboramjet or SST airbreather systems. Principal disadvantages associated with the rocket-ramjet are the fact that for flyback to base, once the vehicle slows down below ramjet operational speed, no propulsive capability exists, so that a dead-stick landing is required.

Secondarily, relatively little work has been done in flight path optimization for mixed power plant vehicles. The Lox/RP-1 rocket with air augmentation, the SST/RP-1 system with the rocket, and the SST liquid hydrogen system with rocket propulsion appeared to be not competitive in this particular comparison. The turboramjet systems stood out in the safety-emphasized analysis and were reasonably competitive in the others. The biggest disadvantages of the turboramjet systems are the long lead time required for engine development (which is a disadvantage only if it results in system availability being later than the desired availability date), and the high cost of engine development. Sonic over-pressure could be a problem but depends on whether the combination of mission requirements and launch site locations would require over-flying of populated areas. The turboramjet, particularly if the fuel-rich turbofan-ramjet version is employed, offers rather low initial gross weight, good capability for cross-range and dog-leg, a high degree of abortability with no periods in the first stage flight profile where abort is not possible, adaptability to runway operation if desired, and substantial contribution to airbreathing technology (whether or not this is an advantage depends on the individual's assessment of the importance of airbreathing technology). If it is assumed that the turboramjet vehicle without a rocket can accelerate to speeds on the order of Mach 8, then an aerodynamic pull-up to low-q staging conditions is possible with only modest loss in speed. One problem with airbreathing systems (particularly important in the case where cross-range or dog-leg are employed) is the requirement for a guidance and flight control system to provide staging conditions at precisely the right speed and altitude, at precisely the right time (at least within the tolerances normally associated with rocket vehicles), in order to achieve a rendezvous objective.

One may legimately question whether a criteria analysis, such as the one presented, will make any contribution toward the problem of decision making and selection of vehicle configurations. A variety of reasons may be proposed why they will have no discernible effect; for example, (a) selection decisions may be made by a management group not familiar with the techniques, not interested in them, and

further, having their own preference, and not about to change their minds; (b) non-technical factors may be paramount in arriving at a selection; (c) a single criterion, such as cost or gross weight, or rapid system availability, may be completely dominant. Regardless of these objectives, it is probably significant that such a criteria analysis (or any other criteria analysis employing a variety of criteria) brings out the fact that a large variety of factors can be given consideration in choosing a preferred system, and that such an analysis tends to indicate, in a semi-quantitative way, which criteria favor which kinds of systems and to what degree.

Three additional first stage propulsion concepts should be mentioned. The **supersonic combustion ramjet (scramjet)**, or convertible ramjets capable of operating in supersonic combustion mode, may in the future offer very significant advantages because of their capability to operate in airbreathing mode up to high flight speeds. Attractively low gross weights may be possible, and single-stage-to-orbit capability is not out of the question. However, the structural material technology required is well beyond today's state-of-the-art. Scramjets were not considered in this analysis because sufficient data do not exist at the present time to provide real confidence in vehicle performance. Propulsion systems involving air liquefaction, collection, and enrichment were not evaluated because it is the writers' opinion that the complications and development problems associated with these types of systems would be justified only in a case where no other system can meet the mission requirements. Because of the unique characteristics of air-collection schemes, it is relatively easy to specify a mission requirement, involving extensive cross-range capability, which cannot be reasonably performed with other systems on a directly comparable basis; however, it is the writers' opinion that consideration of multiple basing and multiple launches with simpler systems should be included in comparisons with air-collection schemes. The previously stated guidance problem applies here. Advanced composite engines also were not considered. A preliminary analysis by Lockheed of the Marquardt ejector-ramjet cycle did not show it to be superior to a rocket-ramjet vehicle with which it was

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compared. However, analysis of these composite systems can be quite sensitive (sometimes in a non-obvious way) to initial assumptions. Much further technology work and analysis need to be accomplished on composite cycles before they can be properly evaluated for vehicle application.